STS-104/ET-109 Flight Readiness Review

External Tank Project

June 28, 2001

Overview	Presenter G. Wadge-LMSSC/ET	
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- **Limited Life Component Status**
  - All items within required life
- **No Significant Changes**
- **Significant Processing Anomalies**
  - LO2 Tank Dome Weld Repair
- **Special Topic**
  - Cracks in ET-117 LH2 Tank Barrel Panel Ribs
- **Waiver Status**
  - 95% Launch Probability Requirement
    - LO2 tank ogive has foam thickness below the minimum necessary to comply with the “95% launch probability” requirement (NSTS 07700, Vol. X, para 3.2.1.2.14)
      - Reduced foam thickness results in a minor decrease in launch probability due to ice formation (93.3% vs 95% required)
    - Waiver to requirement was approved for ET-102 & ETs 107-110
      - PRCBD S071290 (03/10/00)
- **Readiness Statement**

LO2 Tank Dome Weld Repair

- **Issue**
  - Non-standard initial weld of LO2 tank dome gore weld ODG-11 resulted in low weld elongation (≈1.0%) which drove unique full length repair
      - No parameter violations were noted for any pass
    - Required use of standard 1" and wide panel (18") data to demonstrate repair weld properties

LO2 Tank Dome Weld Repair

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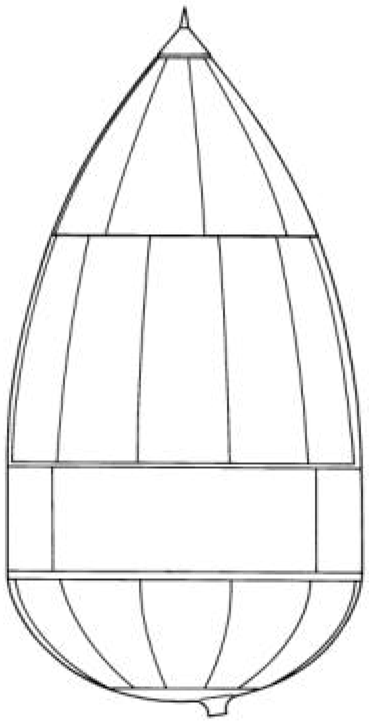
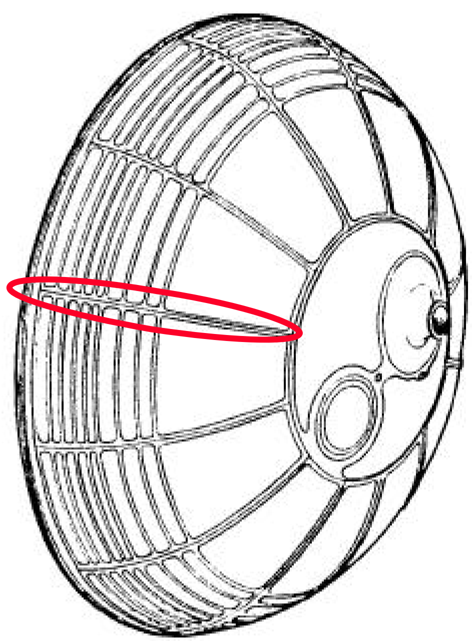
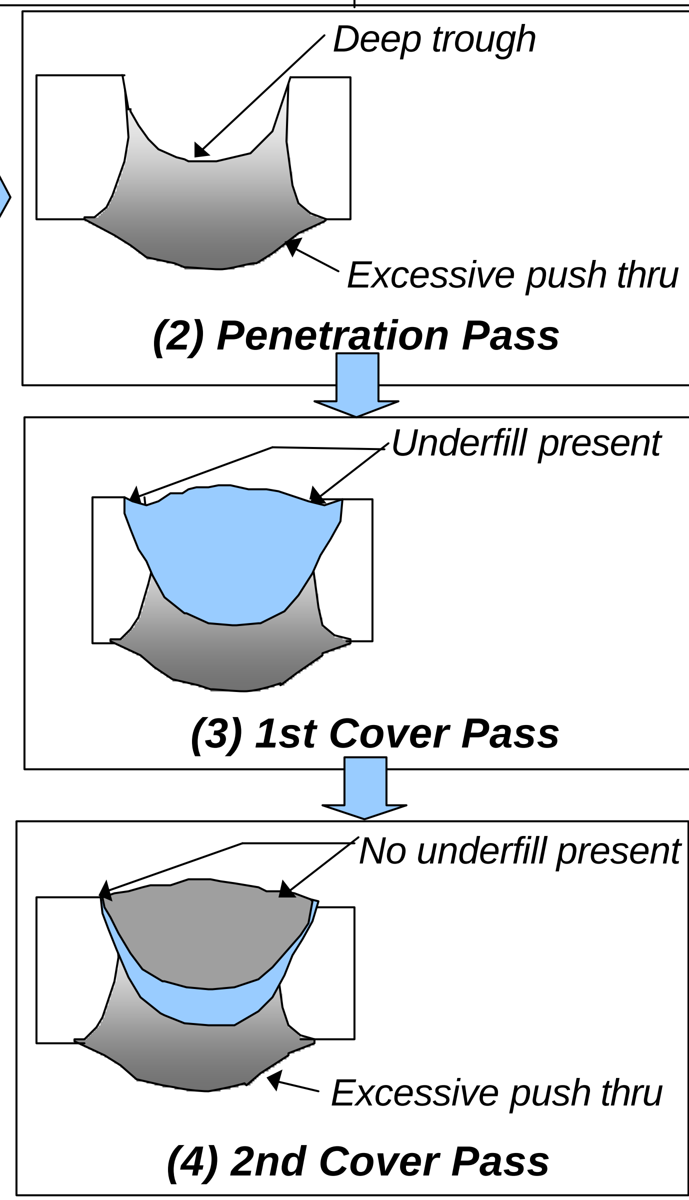
- **Background**



LO2 Tank



LO2 Tank Dome



LO2 Tank Dome Weld Repair

- **Actions Taken**
  - Sectioned cores from ODG-11 flight hardware for macrostructure comparison to test panels
  - Test panel results:
    - Disparity in elongation
      - Some test panels produced 1.5 - 2.0% elongation @ RT and 0.5 - 1.0% @ -320°F
      - Typical initial welds produce values of 4.0-6.0% @ RT and 3.0-5.0% @ cryo temperature
      - Typical repair welds produce values of 4.0-5.0% @ RT and 2.5-4.0% @ cryo temperature
  - Evaluated series of repair options to increase overall elongation of weld
  - Selected optimum full length repair method
    - Maintained acceptable tensile properties
    - Produced acceptable elongation
      - No reduction in elongation in shaved condition

LO2 Tank Dome Weld Repair

- **Discussion**
  - Repair option development panels and repair simulation wide panels demonstrate repair strength capability and elongation
    - Test 1" samples from repair option development results
      - *Ultimate tensile strength*

	RT Actual (ksi)	RT Required (ksi)	Cryo Temp (-320°F) Actual (ksi)	Cryo Temp (-320°F) Required (ksi)
• Average	42.2	N/A	49.5	N/A
• Minimum (ksi)	39.7	30.0	45.2	35.0

      - *Elongation*

	RT	Cryo Temp (-320°F)
• Average	5.4	3.4
• Minimum	5.0	2.0

Note: Results correlate with standard repair weld data

    - Wide panels (required for combined full length repair and additional local repairs)
      - Ultimate tensile strength (panels proofed to 30 ksi @ RT)
      - Panels tested at cryogenic temperature (-320°F)

	Actual (ksi)	Required (ksi)
• Panel #1	41.3	35.0
• Panel #2	53.2	35.0
• Panel #3	47.4	35.0

LO2 Tank Dome Weld Repair

- **Rationale for Acceptance**

  Presented to / accepted by MAF and MSFC Senior Management Review Boards

  - *First time full length repair using 4 additional weld beads at initial weld fusion lines*

- Similarity
  - Core holes have been repaired 2x on SLWTs (excluding this instance)
  - Technique used for core holes repair previously demonstrated > 20 times on SLWTs
    - Other reasons for this type of repair include weld blow through and tail out
- Test
  - Welds are adequately proof tested (assures > 4 mission lives based on standard fracture assessment)
  - Proof test demonstrates > 117% of flight limit load based on a strength assessment (temperature corrected)
  - Panel testing showed repair met or exceeded design repair weld strength and elongation values
    - Repaired core hole included in test samples

Rationale for Acceptance (continued)

- Analysis
  - Fracture
    - Repaired weld meets typical repair weld strength and elongation (in-family)
    - Post proof x-ray and penetrant inspection (ISL and OSL) of repair was acceptable
    - In-family repair enveloped by repair weld fracture data base
  - Stress
    - Standard weld analysis performed for proof and flight conditions
      - Used as-built measured peaking and mismatch
      - Used standard weld repair allowables verified by test
        - Assessed strain levels for ODG-11 weld since strain capability was initially concern
    - Results
      - FS = 1.32 (1.26 required)
        - Maximum predicted weld strain < 1.0%

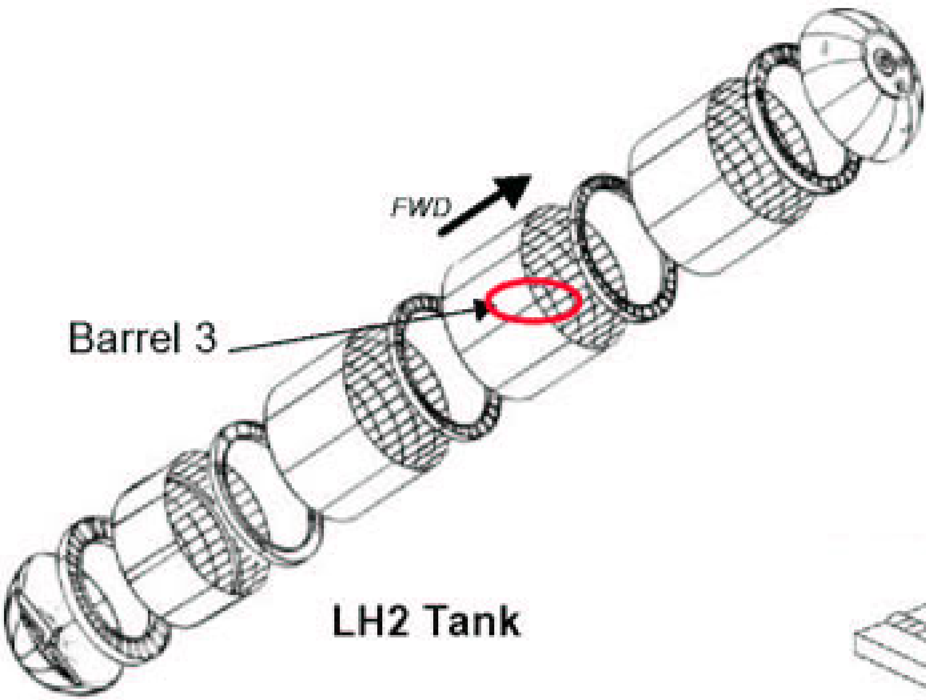
Cracks in ET-117 LH2 Barrel Panel Ribs

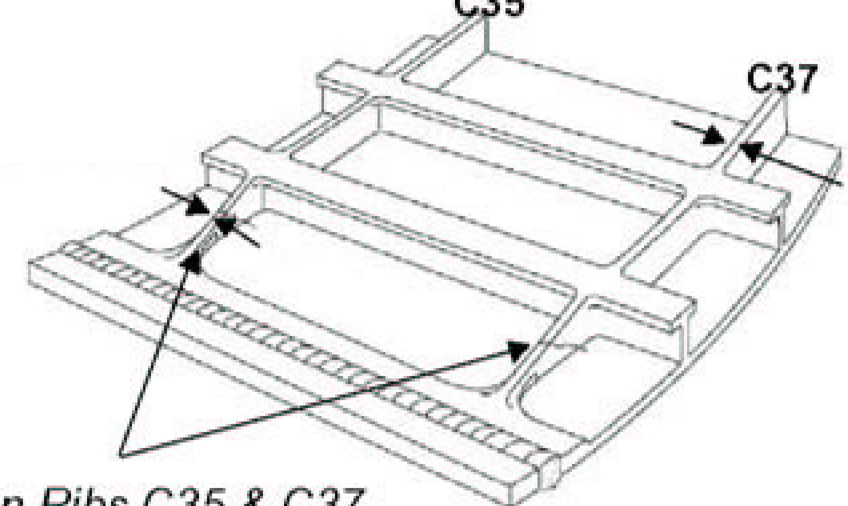
- **Issue**
  - Two cracks were found on LH2 Tank Barrel #3 during the first step of a planned post-proof visual inspection
    - The cracks were on two internal circumferential orthogrid ribs and went through the thickness of the rib and were approximately 1.00” long at the ISL (inner skin line)
    - ISL (inner skin line) observations
      - Cracks were similar in geometry
        - Indicates that ribs experienced similar stress condition
      - Cracks extended into the membrane
      - No other visible damage
    - OSL (outer skin line) observations
      - Dimple noted with visible indication at the rib (C37) location
      - Various minor scuff marks noted in the region of ribs C35 and C37

Cracks in ET-117 LH2 Barrel Panel Ribs

Presenter M.Quiggle-LMSSC/ET

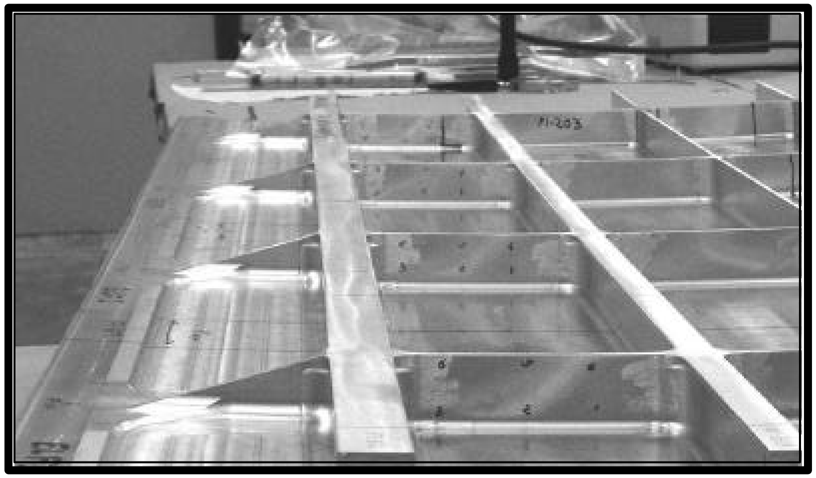
Date June 28, 2001



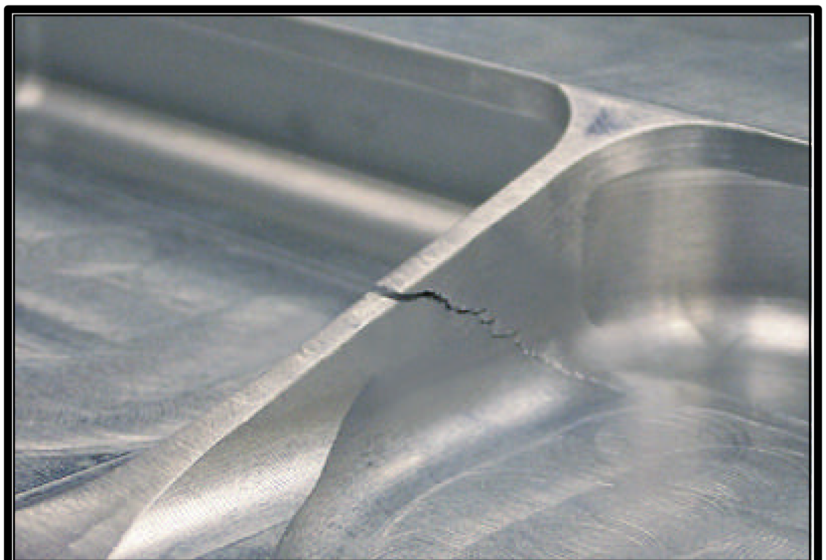


Crack Locations on Ribs C35 & C37
Approx. 45° from +Z at Sta. 1400

Cracks in ET-117 LH2 Barrel Panel Ribs



Typical Orthogrid Configuration



Crack on rib C35

Crack on rib C37

Background - Inspection

- **Planned Post Proof Inspection of the Internal LH2 tank**
  - Practitioners vacuum and systematically wipe each of the individual orthogrid surfaces in the barrel panels
    - Approved processes are used to remove chips, contamination, fingerprints, dust, raised metal or other imperfections on the panels
  - Quality Control inspectors then perform a close inspection
    - All surfaces of the orthogrid panels are systematically reviewed for damage and cleanliness
  - Cleaning and inspection takes approximately 5 minutes per orthogrid pocket (total of 470 hours per LH2 tank) and is accepted by panel quadrant
  - DCMA performs a visual inspection for damage and cleanliness
- **Special Investigation Inspections of LH2 Tank Barrel Panels**
  - Total of 261 barrel panels were inspected for similar damage / indications
    - Panels in storage at MAF
    - 2 post proof LH2 tanks, 3 in-process LH2 tanks and 9 welded barrels
    - All other ET-117 panels
  - No similar damage / indications observed

Investigation Approach	Presenter	M.Quiggle-LMSSC/ET	
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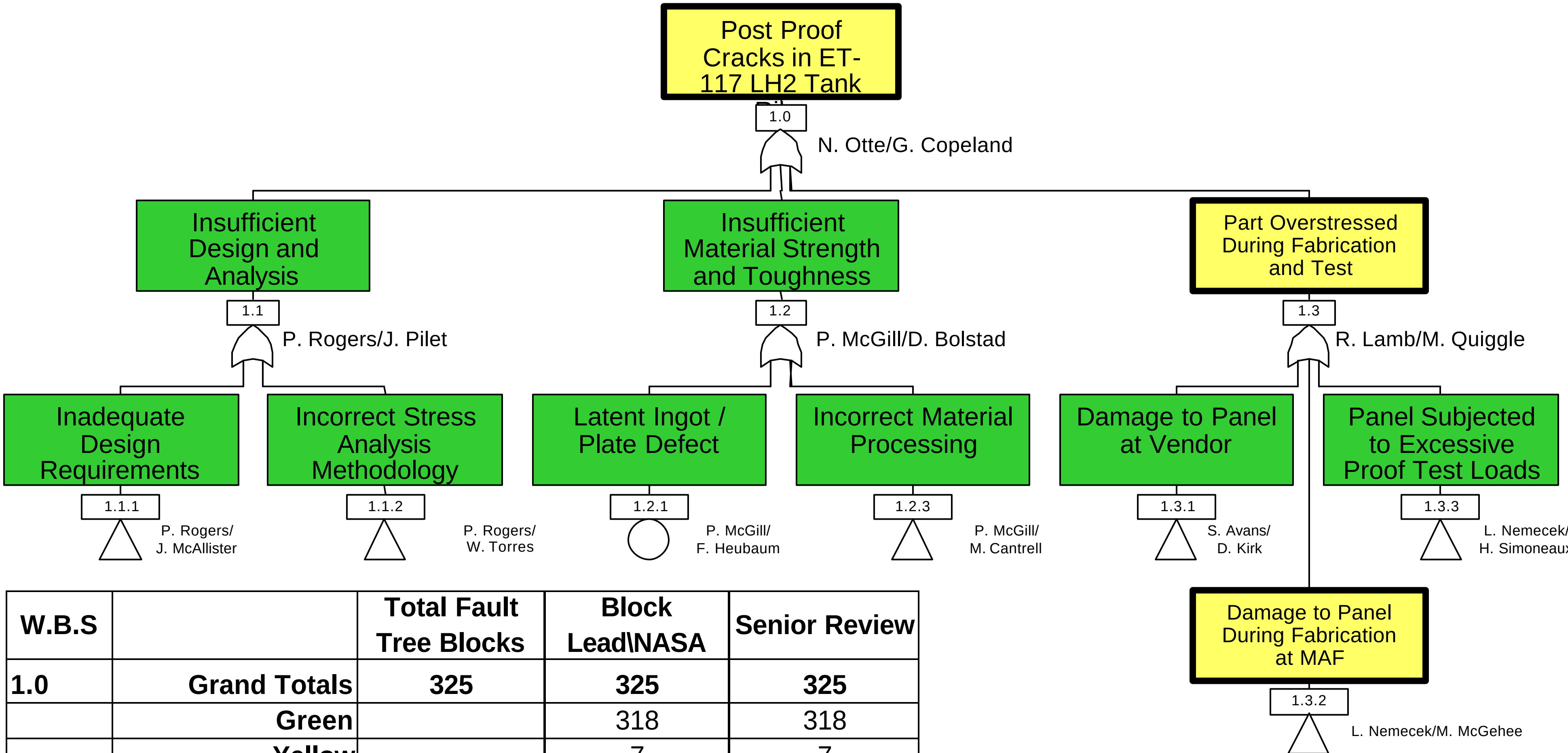
- **A joint NASA/LMSSC Fault Tree team, consisting of senior personnel, was established to determine cause of the two cracks**
  - The team is co-chaired by the NASA and LMSSC Chief Engineers (Neil Otte/Gale Copeland)
  - Multi-disciplined NASA/LMSSC team included members from Engineering, S&MA, Production Operations, Materiel and Facilities

- **Senior Board assembled to review / oversee methodology, technical accuracy and logic used in fault tree development and closure**
  - Robert Schwinghamer - NASA, MSFC Associate Director, Technical (retired)
  - Carmelo Bianca - USA; former NASA, MSFC Fracture Control Board Chairperson
  - Richard Foll - Lockheed Martin, Technical Operations Vice President (retired)
  - Jon Dutton - Lockheed Martin, ET Project Vice President (retired)

Investigation Approach

- **Used fault tree methodology to develop a systematic and thorough approach for problem investigation**
  - Fault tree addressed all aspects of barrel panel life cycle
    - Design, material, fabrication and handling processes
      - Re-verified compliance with design and material requirements
      - Retraced panel life cycle to establish potential contributors to damage
        - Reviewed as-built configuration documentation
        - Reviewed processing timelines
        - Interviewed practitioners
  - Performed top level tests to establish extent and nature of damage
    - Performed helium leak check with local vacuum – Background helium levels detected
    - Returned ET-117 LH2 tank to proof test facility
      - Strain gage data at 9 psig
      - Leak check with GN2 at 6 psig resulted in no leaks
    - Failure analysis of cracks
      - Simulated service test of ET-117 C35 and C37 flaws showed that this tank would have survived 4 missions (56 cycles) with residual strength equivalent to 180% of flight stress

Fault Tree Top Level Structure



W.B.S		Total Fault Tree Blocks	Block Lead\NASA	Senior Review
1.0	**Grand Totals**	**325**	**325**	**325**
	Green		318	318
	Yellow		7	7

Green = Not a Contributor

Yellow = Indeterminate Cause / or Contributor

Fault Tree Analysis (1.1)
Insufficient Design / Analysis

W.B.S		Total Fault Tree Blocks	Block Lead\NASA	Senior Review
1.1	**Totals**	**21**	**21**	**21**
	Green		21	21
	Yellow		0	0

- **Summary of Fault Tree Findings**
  - Inadequate Design Requirements
    - All engineering / design requirements were re-verified to match analytical models
    - No new engineering requirements were implemented at ET-117
  - Incorrect Stress Analysis Methodology
    - Stress analysis model input was re-verified
    - Correlation of model with structural testing performed during SLWT Verification Program was re-verified
    - The non-linear FEM analysis and 9 psig test strain gage data were used to provide additional stress model verification
    - Local NASTRAN non-linear FEM analysis of barrel panel confirms previous model results
      - Analysis shows relatively low stress levels at crack locations for maximum proof loading
      - Higher stress levels exist in general acreage membranes
  - Engineering design and analyses were re-verified
  - Stress analysis model was re-verified using previous structural test data, local non-linear FEM and strain gage data from ET-117

Design / Analysis was re-verified.
Not a contributor to circumferential rib cracking.

Fault Tree Analysis (1.2)
Insufficient Material Strength and Toughness

W.B.S		Total Fault Tree Blocks	Block Lead\NASA	Senior Review
1.2	**Totals**	**12**	**12**	**12**
	Green		12	12
	Yellow		0	0

- **Summary of Fault Tree Findings**
  - Latent Ingot/Plate Defect
    - Review of Reynolds Metals ultrasonic test showed no out-of-spec internal defects
    - Examination of C35 and C37 fracture faces showed no latent defects
  - Incorrect Material Processing
    - Heat treat was correct
      - Records showed no out-of-family processing
      - Certification and witness panel results met strength requirements
    - Wet chemistry of sample from barrel panel was within specification requirements
    - Metallographic samples showed typical 2195-T8 microstructure
    - Strength and toughness
      - Tensile test coupons from barrel panel met requirements
      - Samples from ET-117 met the cryogenic simulated service test four mission life requirement
  - Failure analysis of the two cracked ribs and surrounding area did not reveal any material anomalies
  - ET-117 barrel panel material met all engineering requirements

Material Strength and Toughness was re-verified.
Not a contributor to circumferential rib cracking.

Fault Tree Analysis (1.3)
Over-Stressed During Fabrication and Test

W.B.S		Total Fault Tree Blocks	Block Lead\NASA	Senior Review
1.3	Totals	292	292	292
	Green		285	285
	Yellow		7	7

- **Investigation focused on Fabrication and Test processes which could result in an over-stressed condition**
  - Fault tree followed the panel from vendor machining through MAF processing
    - Major fault tree block headings were
      - Damage to Panel at Vendor (1.3.1)
      - Panel Subjected to Excessive Proof Test Loads (1.3.3)
      - Damage to Panel During Fabrication at MAF (1.3.2)

Fault Tree Analysis (1.3.1)
Damage to Panel at Vendor

W.B.S		Total Fault Tree Blocks	Block Lead\NASA	Senior Review
1.3.1	**Totals**	**55**	**55**	**55**
	Green		55	55
	Yellow		0	0

- **Summary of Fault Tree Findings**
  - Review of certification / build data for suppliers showed no “out-of-family” or anomalous conditions existed
  - Conducted comprehensive review of critical processes to identify potential for anomalies
    - Review included processes and tooling for machining, forming, etch and penetrant, and handling during transportation
    - Identified opportunity for a non-standard over-formed condition during forming at vendor
      - A detailed study was conducted at AMRO of forming tools and processes
      - Tests conducted to achieve significant over-forming
        - Over-forming resulted in obvious panel anomalies
        - Re-verified brake press and contour check fixture satisfied requirements
  - Vendor tooling, processes, and paper were re-verified to meet engineering / design and fabrication requirements
  - No new engineering requirements implemented at ET-117
  - Build paper review showed all requirements were satisfied

Vendor tooling, processes and paper were re-verified.
Not a contributor to circumferential rib cracking.

Fault Tree Analysis (1.3.3)
Panel Subjected to Excessive Proof Test Load

W.B.S		Total Fault Tree Blocks	Block Lead\NASA	Senior Review
1.3.3	**Totals**	**28**	**28**	**28**
	Green		28	28
	Yellow		0	0

- **Summary of Fault Tree Findings**
  - A detailed study was conducted of proof test tools, processes and handling
    - ET-117 proof test pressures, loads, and deflections were within requirements and in family with prior LH2 tank proof tests
    - Proof test equipment (i.e. PLC, hydraulic cylinders, pressure transducers) were within calibration limits and re-calibration dates
    - Crew interviews showed no anomalies during tank transportation or performance of proof test
    - No handling processes and controls issues identified
    - No change in personnel from previous proof tests
  - No new engineering requirements implemented at ET-117

Proof test alone could not have produced circumferential rib cracking.

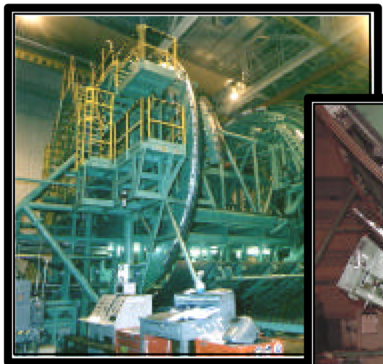
Fault Tree Analysis (1.3.2)
Damage to Panel During Fabrication at MAF

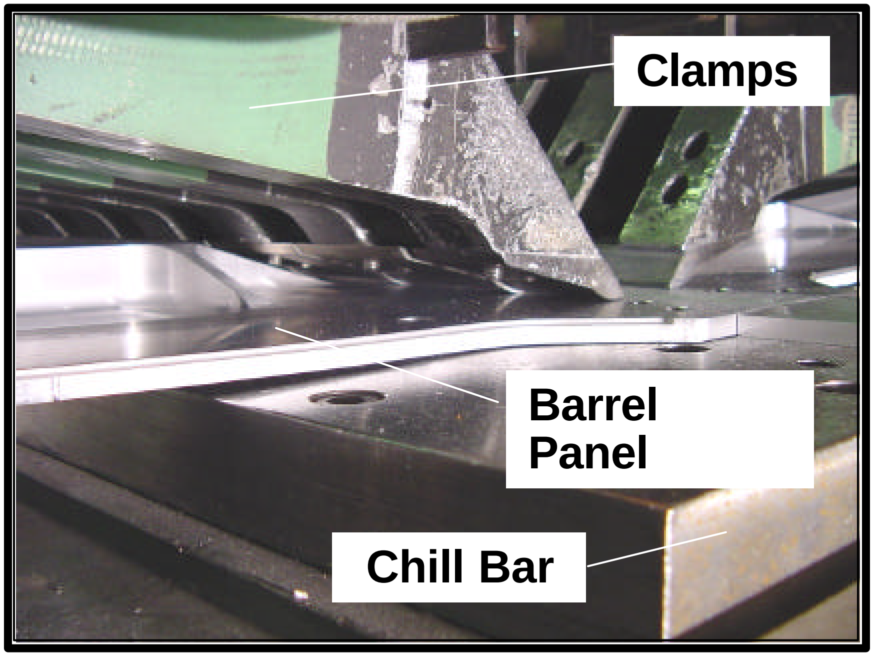
W.B.S		Total Fault Tree Blocks	Block Lead\NASA	Senior Review
1.3.2	**Totals**	**208**	**208**	**208**
	Green		202	202
	Yellow		6	6

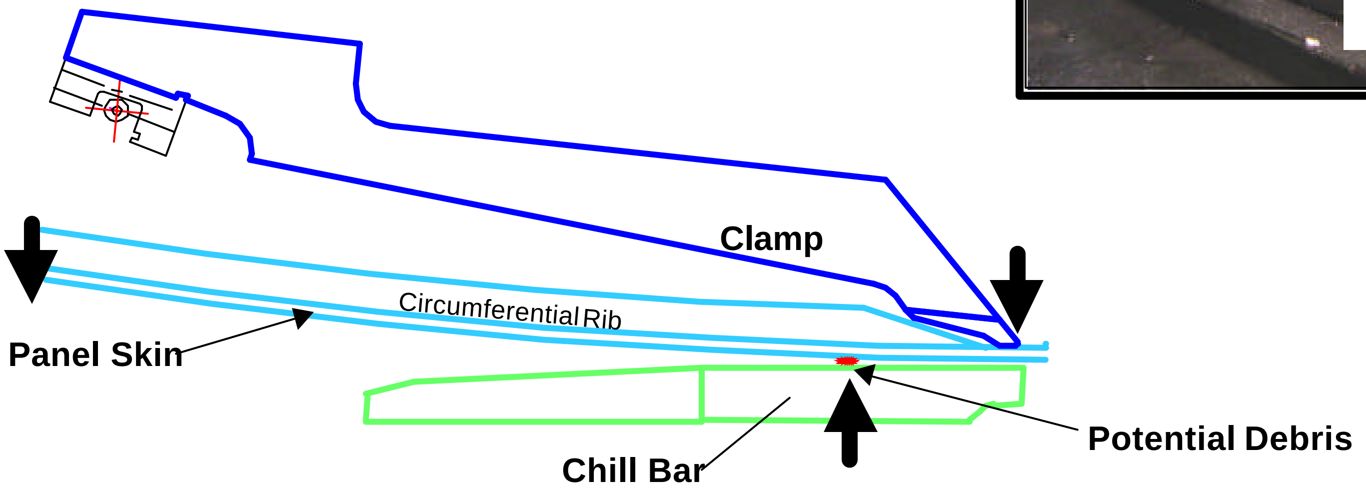
- **Summary of Fault Tree Findings**
  - A review of certification / build data for ET-117 showed no "out-of-family" or anomalous conditions existed
  - No correlation found between facility work in the plant and the location of the completed barrels
  - A detailed review was conducted of tools and processes
    - Review covered the time from panel received at MAF to the completed tank ready for proof test
    - In process fabrication and handling activities were witnessed by the team to provide insight as to potential causes or contributors
    - Tests were conducted on specific tools to create conditions that could have been causes or contributors
  - Cracks could not be attributed to documented processing
  - Nine undocumented scenarios were hypothesized
    - Resolution plans were initiated to determine which scenarios were credible
  - Six were eliminated by tests and analyses
  - Three were determined to be possible contributors

Evaluation of Potential Cause Scenarios

- **Improper Clamping of Panel in Longitudinal Barrel Weld Tool**







- **Potential Cause Scenario #2**
  - Inadvertent Object Obstruction During Tank Rotation in Major Weld Tools

  - An object is accidentally located against the tank
  - The object must be smooth and have sufficient stiffness and cross-sectional area to affect two ribs without permanently deforming the tank OSL
  - The object obstructs the tank rotation causing deflection of the tank wall resulting in cracked ribs
  - The load required to crack the ribs is estimated at approximately 1000 to 3000 pounds

Inadvertent object obstruction during tank rotation could result in circumferential rib cracking.

Evaluation of Potential Cause Scenarios

- **Inadvertent Object Obstruction During Tank Rotation in Major Weld Tools**

Evaluation of Potential Cause Scenarios

- **Potential Cause Scenario #3**
  - Inadvertent, Unreported Impact

  - An object accidentally strikes a completed barrel or Tank assembly
  - The object must be smooth and have sufficient mass, velocity, and contact area to affect two ribs without permanently deforming the tank OSL
  - The object deforms the tank and cracks the ribs
  - The load required to crack the ribs is estimated at approximately 1000 to 3000 pounds

Inadvertent, unreported impact could result in circumferential rib cracking.

Fleet Clearance Rationale	Presenter M.Quiggle-LMSSC/ET	
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- **Fault Tree Analysis**
  - ET design and materials were exonerated as contributors to ET-117 anomaly
  - Rigorous review of process instructions for post proof processing found no inadequacies
  - Fault tree and fracture face analysis concluded that the ET-117 damage event occurred during processing, prior to the proof test
    - The cracking could have occurred either prior to or during the proof test
      - Prior residual stress required for cracking during proof test
  - First of three planned post-proof cleaning and inspection steps identified cracks

- **Flight Rationale**
  - Fault tree team and Senior Review Board concluded that this was an isolated event and not the result of a systemic problem
  - Investigation validated proof test and post-proof inspections for certification of tanks

Readiness Statement	Presenter	
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The External Tank, ET-109, is certified and ready for STS-104 flight pending completion/closure of open and planned work